VCT

AN INVENTION THAT WILL CHANGE THE FACE OF ELECTRONICS

Ron Harris, from our London office, went to talk to Professor Gosling of Bath University about this new device about to be released by Texas Instruments.

THE BASIC OP-AMP HAS BEEN WITH us since the days of the valve, and when semiconductors crept up on us, it was simply re-designed to use transistors. This, in the opinion of many designers, means that the advantages of transistors are not being fully exploited.

BASIC IDEAS

One of the better improvements to the basic op-amp was the comparator input designed by Carl S. Brinkler – a name to which we shall return – and patented in April 1965. However Mr. Brinkler was still dissatisfied with the op-amp and some years ago began discussions with Professor Gosling, with a view to producing a totally new circuit block. The basic guidelines were finally set as being that

1. No feedback should be needed to stabilise the device by limiting the high frequency response, or to define the stage gain.
2. Both the input and output ports must be totally floating – a true four terminal device. This leads to much greater freedom with respect to the output – it can quite simply be fed into anywhere!
3. The output should be a constant current source i.e. very high impedance. Then, should a voltage output be required at any time, a resistor need only be inserted across the port.

TEXAS AND THE PROTOTYPES

In 1974 Texas Instruments authorised Carl Brinkler to undertake research into producing such a device. Because of the scope and magnitude of the task, it was to be a joint undertaking with Bath University, i.e. Professor Gosling. In the autumn of 1974 the microcircuit design was breadboarded up for the first time with discrete components, and early in 1975 the first ICs rolled out of the ovens. The first vast improvement over the op-amp to become apparent was the slewing rate, up to 20V per microsecond, as compared to 0.5V per microsecond for the 741.

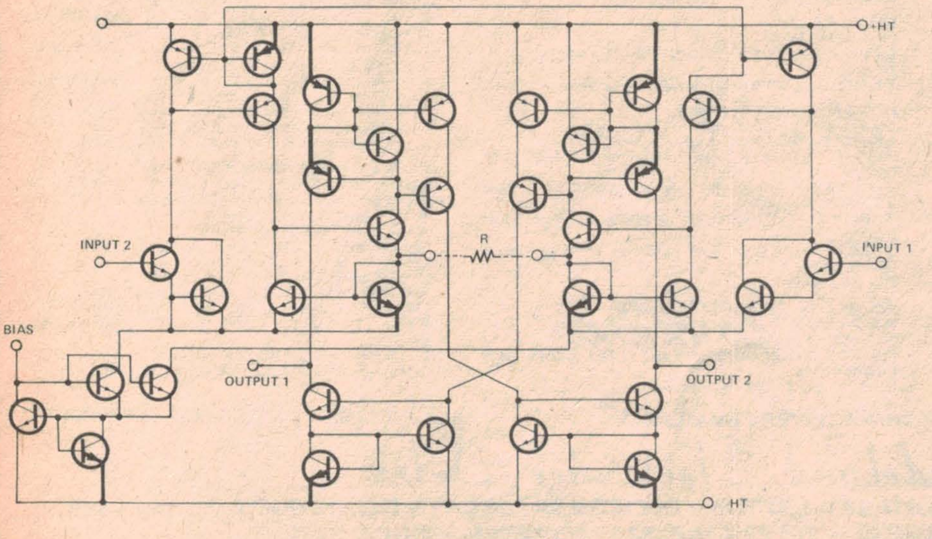


Fig. 1. Internal circuit of the prototype VCT. The 'R' in the middle is external.

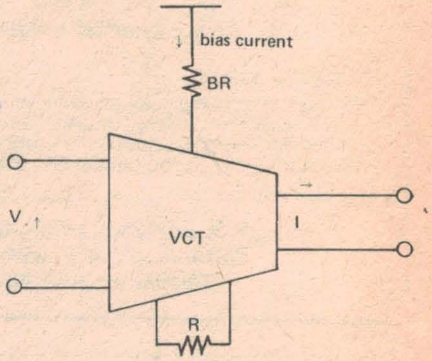


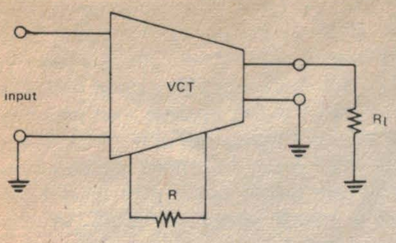
Fig. 2. The agreed symbol for VCT.

The offset on these prototypes was ≏10 mV, due to the layout not being totally symmetrical. Production models, when they appear, will have a much much lower offset. Up to this point in the proceedings the project had been running on a shoe-string. But with the prototypes showing this incredible potential, Texas whipped the whole show off to Dallas for development. They feel the VCT is the greatest advance in circuit design for a long time, and we have to agree with them.

ABILITIES IN CIRCUIT

Let's take a look at what the VCT will do. Figure 1 shows the internal circuit of the Mark 1 VCT. The thick lines represent multiple emitters, and these provide the current gain. You may recognise the current mirrors around the top centre of the circuit.

The agreed symbol for the VCT is shown in Figure 2, the circuit is that used for all linear applications. For a voltage input, we get a pure constant



Voltage gain = k. RL/R.

Fig. 3. VCT as a non-inverting amplifier.

current output. Both input and output impedances are very high, around tens of megohms in the production devices.

There is a fixed ratio between V_{in} and I_o, which is set by one fixed resistor R, i.e. $I_o = k/R\ V_{in}$. The constant k can be designed to be any value – it will be four in the Texas VCTs. A bias current is applied down BR, and the device can only output twice as much current as it draws through BR. Early devices will be 20 mA output VCTs, but later marks will be up in the amps range. A ±15V rail is used with the VCTs, and a ± 13V is quite permissible!

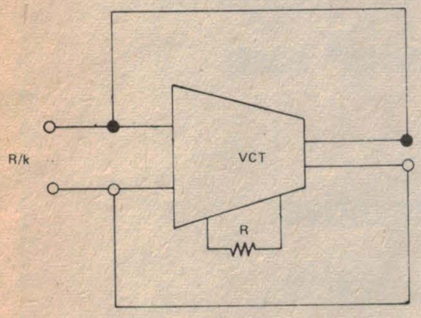


Fig. 4. VCT as a simple resistor.

Some circuits now, for instance an amplifier, see Figure 3. The simplicity of gain inverting arises because the output port naturally has a fixed phase relationship to the input. Since we get a current out for a voltage, a VCT connected as in Figure 4 will look like a resistance, value R/k ohms.

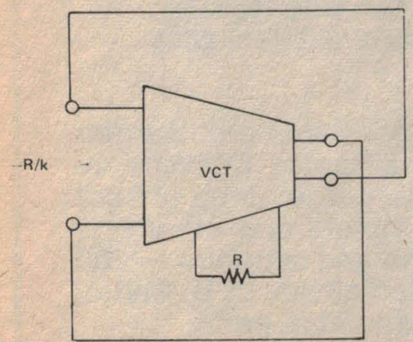


Fig. 5. VCT working as a negative resistance.

Consider however a device cross connected as in Figure 5. What we have now, looking in at the input terminals, is no less than a negative resistance! I.E.,

$$V_{in} = -\text{const.}I_o.$$

What's more, the transfer characteristic is perfectly linear!

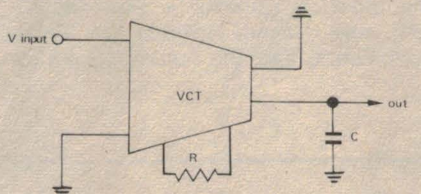


Fig. 6. VCT as an integrator.

Applications are literally infinite. Anything an op-amp can do, so can a VCT – only usually it does it better! For instance an integrator, see Figure 6. At point A we have $\int V_{in}\,dt$ since the output is a constant current which follows the input voltage. If we feed back this integral to the input as in Figure 7, the output will be the differential of V_{in}.

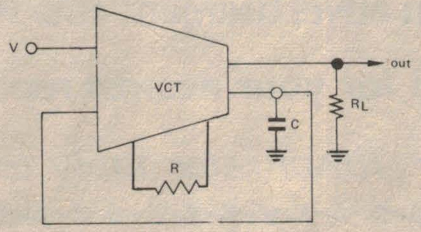


Fig. 7. VCT differentiator.

Gyrators are by now quite commonplace, but what about one which can reach inductor values of tens of Henrys and with a Q of well over 100? Easy!

Values of Q up to 200 have been achieved experimentally. This circuit introduces the concept of using two VCTs together.

Texas are packaging the VCT in a 16-pin DIL dual package. There are more pins to a VCT than a 741, since we have those already mentioned, plus a centre tap on the output which is not always used, but extends the versatility.

The application we found initially most amazing is the VCT's ability to replace a transformer, better than a transformer! All transformers exhibit some power loss, but this circuit has a selectable loss factor, which naturally can become a *gain* if so desired.

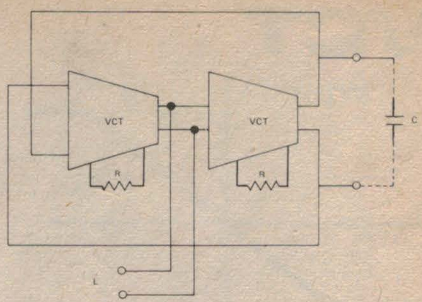
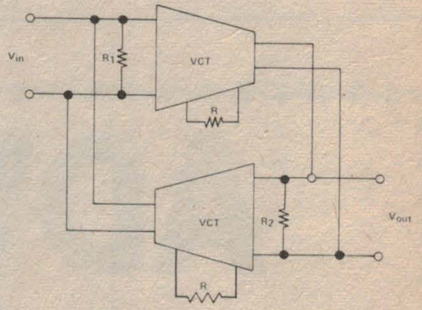


Fig. 8. A VCT gyrator.

Choose R such that $R^2 = R_1 R_2$ to give no loss/gain in circuit i.e. a perfect transformer.



Transformer Ratio = $(R_1/R_2)^{½}$.

Fig. 9. VCT as a transformer.

NON-LINEAR

We will consider just one non-linear application to show it can be done – that of a limiter. Since the VCT can output only 2x bias current with the circuit of Figure 10, we will get a characteristic shown in Figure 11, very simply indeed with only two resistors.

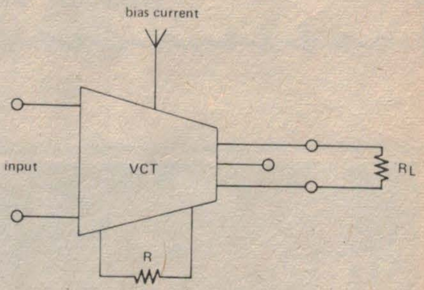


Fig. 10. Circuit to give the characteristics shown in Fig. 11.

GAINS FROM LESS

It is apparent from the preceding circuits that one of the biggest gains when using VCTs, is in reducing external component count over a similar op-amp or discrete circuit. In industrial applications this will lead to less pcb design and assembly complications, with resultant reduction in costs.

Another gain is the fact that when used as an inverting amp, no input resistor is used to drop the signal, as it is in op-amp circuits. In these circuits,

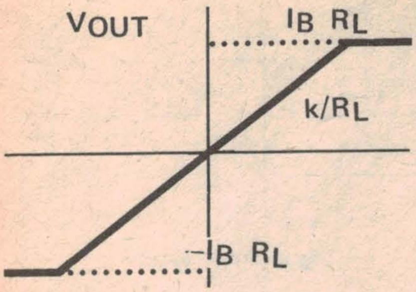


Fig. 11. Characteristics of the circuit in Figure 10.

since the input is usually a virtual earth, most of the signal is dissipated in the resistor, with a resultant poor signal-to-noise ratio upon amplification at the output. With VCTs no resistor is required, and this gives a distinct improvement in S/N ratio, with the attendant gain in dynamic range.

THE PRICE OF A FUTURE

One question remains – how much? Well, this depends entirely on Texas Instruments, and the marketing policy they persue. No doubt the price will be high at first, falling as the volume of sales climbs, as it surely must. Interestingly, the VCT occupies only half the chip area of a 741 op-amp, but whether this affects pricing remains to be seen. We'll keep you informed of developments, as we're convinced you'll be hearing much more of VCT in the years to come.

OUR THANKS and congratulations to Professor W. Gosling of Bristol University, who provided the information for this article.

MORE ON VCT

In the January 1977 issue of ETI Ron Harris reviewed the recent development of the Voltage-Current Transactor (VCT), perhaps the most important device innovation of recent years for not only is the VCT expected to perform all the functions we now expect of the op-amp but to perform them either better or with fewer additional components.

The earlier article briefly covered the VCT's development and its terminal properties, together with basic circuit applications. This article describes the VCT's internal functioning. It has been written for ETI by Dr. J.E. Morris of the Department of Physics, Victoria University of Wellington, New Zealand.

THE CIRCUIT SYMBOL for the VCT is shown in Fig 1 along with the necessary bias supply and an external resistor R which determines terminal gain. The name "voltage-current transactor" is derived from the translation of differential input voltage into a proportional output current.

As with the conventional op-amp, the input impedance is made as high as possible to minimise loading of any practical source of input voltage. but the main difference between the VCT and an op-amp lies in the output port. As a current source rather than one of voltage, the port impedance is high rather than low. Furthermore, whereas the op-amp output signal is usually single-ended and referenced to ground, the VCT output is completely floating.

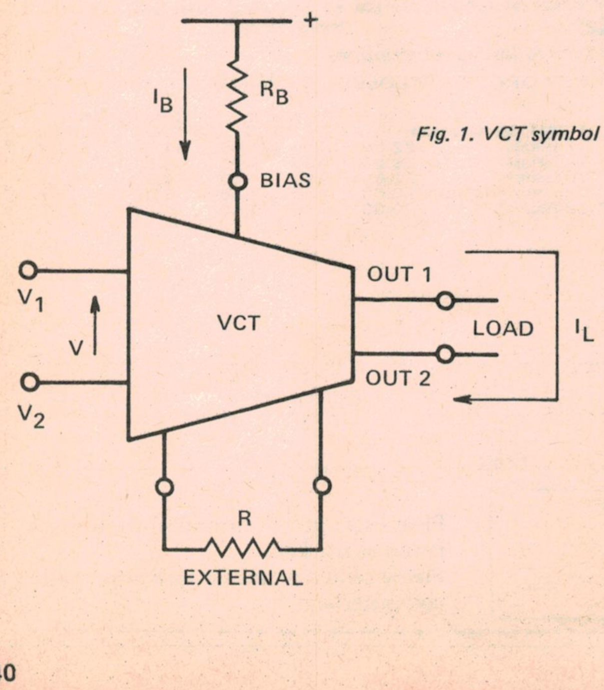


Fig. 1. VCT symbol and external connections.

The VCT is thus a true four terminal device and either terminal of either port may be used as a common point. It will also be apparent from Fig. 1. that there is no external feedback element involved in a simple amplification application.

The internal circuit is shown in Fig. 2. and as explained in this article there is no overall feedback concealed within the unit. With no feedback, there can be no feedback stability problems and thus a major headache of op-amp design vanishes.

VCT Circuit

Modern IC's are generally very complex and involve many functional blocks. At first glance a circuit diagram often appears to have more relevance as a design for a maze than as a sensible means of serving these required electronic functions. The trick is to identify the functional blocks. Once their patterns are recognized, circuit operation may be deduced. For example it is obvious that the VCT is essentially symmetrical about the centre, so only one side need be considered in detail. And the input transistors (Q_1 Q_2 on side 1) clearly form a Darlington pair and may be regarded as a single composite transistor (Q_D say) in any simplified analysis.

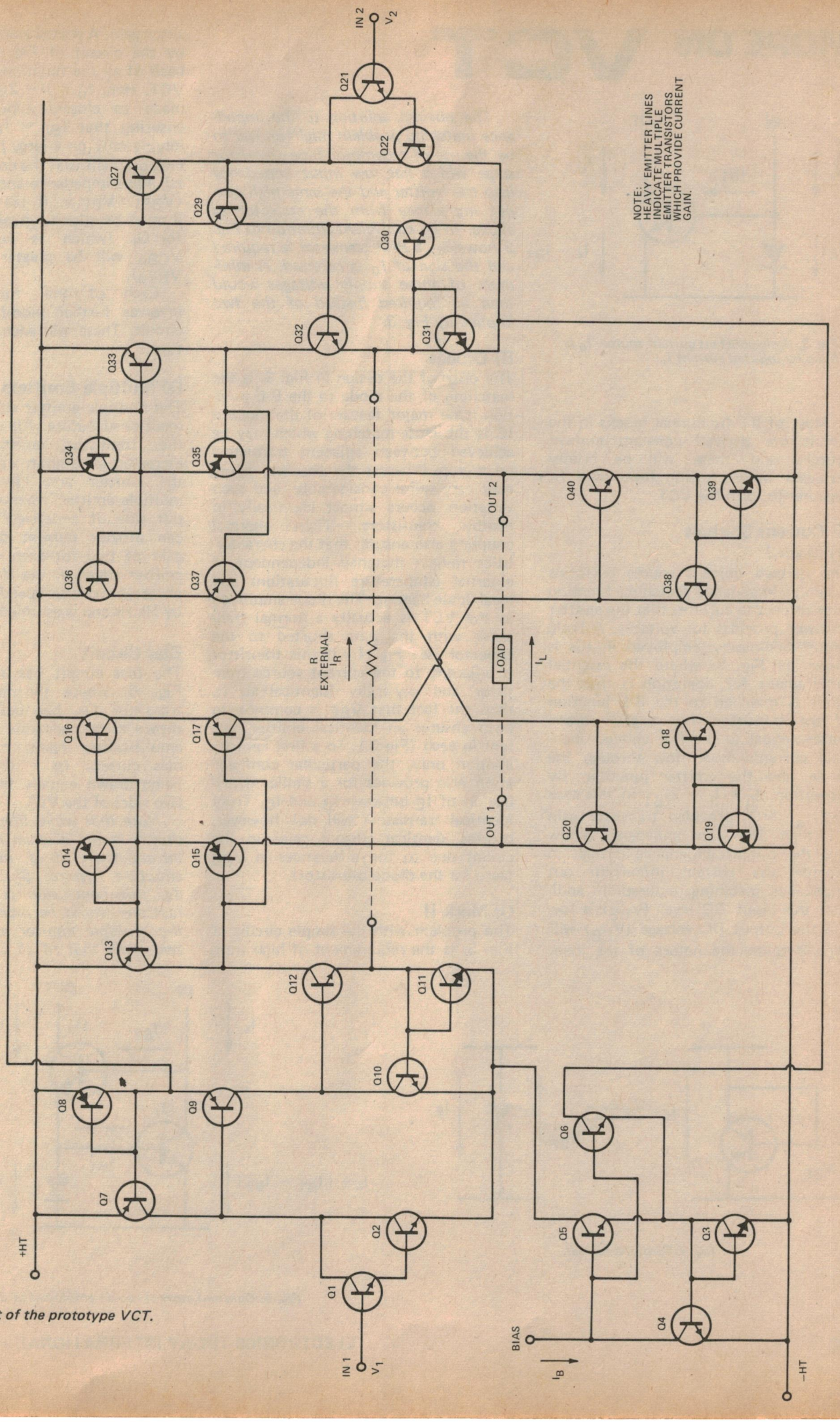


Fig. 2. Internal circuit of the prototype VCT.

MORE ON VCT

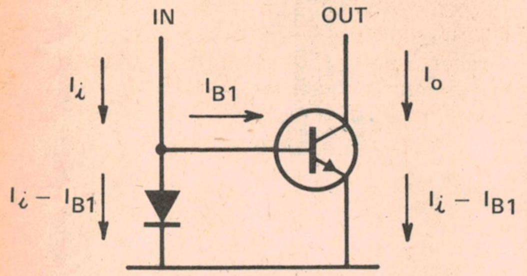


Fig. 3. Basic constant current source. I_O is fixed by injected current I_i.

Most of the functional blocks in the circuit are derived constant current sources and these will be briefly reviewed before seeing how they fit together to form the VCT.

IC Current Sources

A) Mark I

The derived current source performs a similar impedance matching function with respect to currents that the emitter follower provides for voltages. A basic circuit commonly employed in ICs is shown in Fig. 3. where the essential requirement for operation is that the diode is matched to the B-E junction of the transistor. For a given diode voltage equal to the B-E voltage, identical currents must flow through the diode and the emitter junction. By inspection, $I_0 = I_i - 2I_{B1}$ in this case and $I_O \approx I_i$ provided transistor gain β is high. The input impedance is low and the output impedance is high to provide the current in/current out impedance matching required. In addition the input DC level (V_{BE}) is low and the output DC voltage (V_{CB}) will depend upon the nature of the load.

The obvious solution to the impedance matching problem might appear to be the use of a common-base transistor stage which has low input impedance into the emitter and the same high output impedance from the collector as above. In an equivalent situation to Fig. 3 however, a PNP transistor is required and the sign of I_O is reversed. A minimum of three supply voltages would then be required instead of the two implied by Fig. 3.

B) Diodes

The crux of the design in Fig. 3. is the matching of the diode to the B-E junction. One major feature of the modern IC is the close matching which may be achieved between adjacent transistors on a chip. Whereas the absolute values may vary quite considerably, and such variation occurs almost identically in nearby transistors. Tight thermal coupling also ensures that the characteristics remain matched independent of external temperature fluctuations and local Joule heating. The diode employed in the VCT is actually a normal transistor with the base shorted to the collector (see Fig. 4.) If this transistor is adjacent to the current source transistor and plysically identical to it, then the fact that V_{BE} is common to both ensures an identical emitter current in each (Fig 3.). To a first approximation only, the particular configuration also provides for a similar distribution of I_E between I_B and I_C. Truly identical transistors will not, however, possess identical current gains in the circuit due to the differences in V_{CB} (zero for the diode transistor).

C) Mark II

The problem with the simple circuit of Fig. 3. is the requirement of high transistor gain. A partial solution is provided by the circuit of Fig. 5. which is the basis of all the functional blocks of the VCT. Here $I_o = I_i + 2(I_{BI} - I_{B2})$ and is made to closely approximate I_i by ensuring that $I_{BI} \approx I_{B2}$ rather than relying only on a large β. Note that the improvement is at the cost of an increased input impedance and DC input level ($V_{BEi} + V_{BEo}$). If $I_{BI} = I_{B2}$ exactly, β must be slightly greater for Q_o than for Q_i (which is reasonable since V_{CBo} will be greater than $V_{CBi} = V_{BEo}$).

Each of the functional blocks involves further modification of this circuit. These will each be described in turn.

D) Multiple Emitters

The multiple emitter structure has been mentioned before. All it means is that the transistor emitter current is increased for a given V_{BE} by increasing the emitter area. In this way the multiple emitter, when used in the output side of a derived current source, can provide current gain. A current gain of two for each of the multiple emitter stages in the VCT leads to the prototype device specifications quoted by Harris and is assumed below.

Bias Circuit

The bias circuit has been redrawn in Fig. 6. where the multiple emitter transistor Q_3 has been split and is shown as two separate diodes. Current amplification leads to the defined bias current $I_B = (V_S - 2V_{BE})/R_B$ being drawn equally from each of the two sides of the VCT.

Note that while the total symmetry shown in the diagram implies that the introduction of a multiple emitter structure requires β_5,β_6 to be twice β_4, this conclusion is misleading. In fact one would be more likely to vary the multiple emitter area slightly off two, such that (i) all β's were approx-

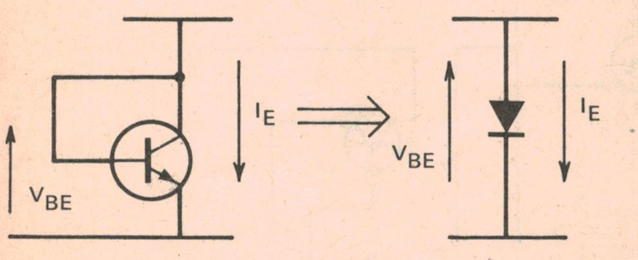


Fig. 4. IC diode format.

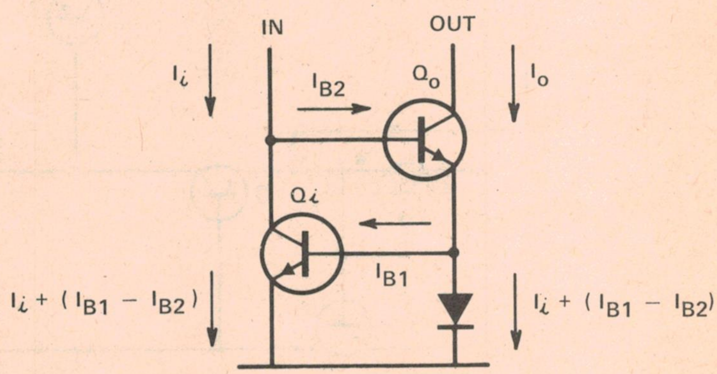


Fig. 5. Constant current source employed in the VCT.

imately equal as before (ii) diode currents become $I_B + \frac{1}{2}I'$, and (iii) the base current of Q_4 reverts to $(\frac{1}{2}I') + (\frac{1}{2}I')$.

Differential Input

It should be clear by now that the VCT relies upon defined current sourcing and multiple emitter current amplification to function. The input signal, however, is defined as a differential voltage ($V_1 - V_2$) and must be converted to a proportional current. This is the purpose of the external resistor R as shown by the simplified view of Fig. 7. where I_R is clearly $(V_1 - V_2)/R$ provided symmetry is maintained. (Q_D is the Darlington combination Q_1 and Q_2,; Q11 functions as a diode.)

It will be seen shortly that the existence of a finite I_R upsets the symmetry — in fact this is how the circuit functions. So once again, our ideal is not quite possible since the diodes carry different currents at slightly different voltages. In fact $I_R \gtrsim (V_1 - V_2)/R$.

The next step is to see how I_R is converted to an output current.

Input Circuit

The input section of one side of the VCT is redrawn in Fig. 8. Q_8 services both sides of the circuit and has been split in the diagram. Assume for the moment that some current I_x flows down through Q_7 and then the Darlington Q_D. The Q_7, Q_8, Q_9 current sourcing circuit requires I_x to also flow through Q_9 and Q_{10}. Similarly Q_{11} should draw $2I_x$ due to the double emitter. The total $4I_x$ must equal the bias current I_B and hence the currents are as shown with Q_{12} also carrying I_B. The principle of this input circuit is summarised for reinforcement in Fig. 9. which should be compared with Figs. 7 and 8.

It has already been stated that V_{CB} of the source output transistors will vary under operating conditions and

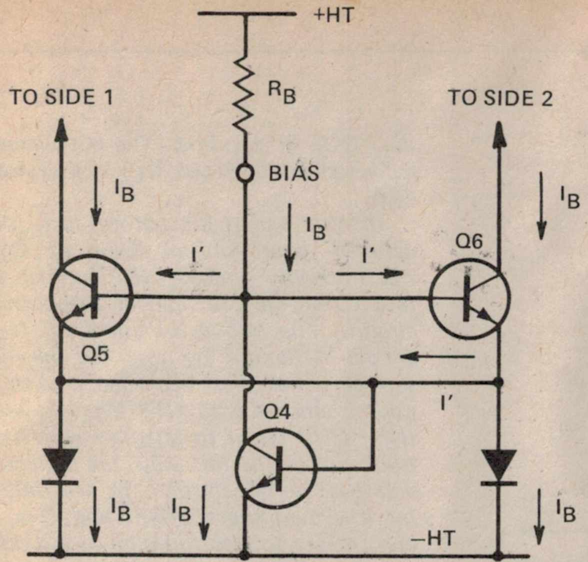


Fig. 6. Bias circuit as an example of the multiple-emitter diode.

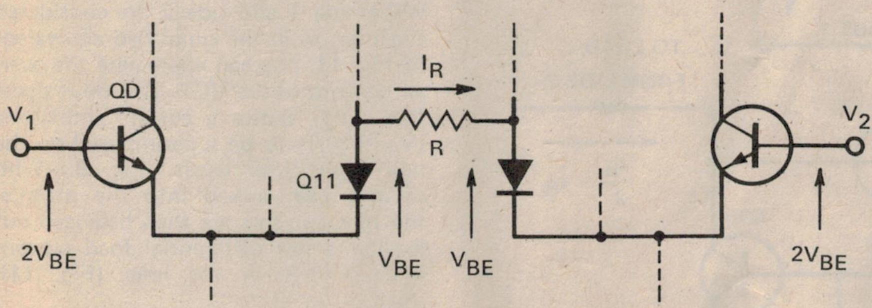


Fig. 7. Simplified view of the differential input circuit.

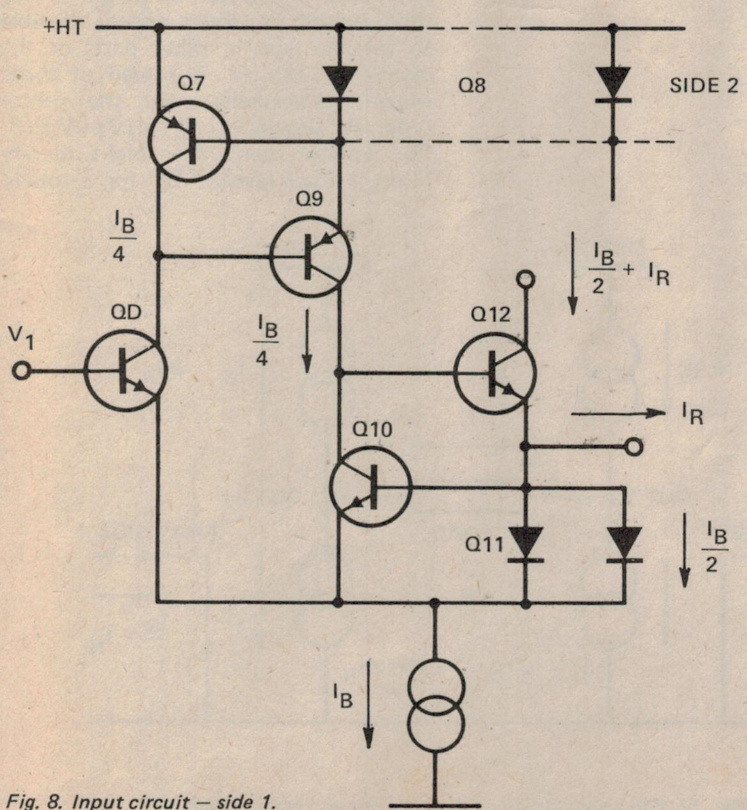


Fig. 8. Input circuit — side 1.

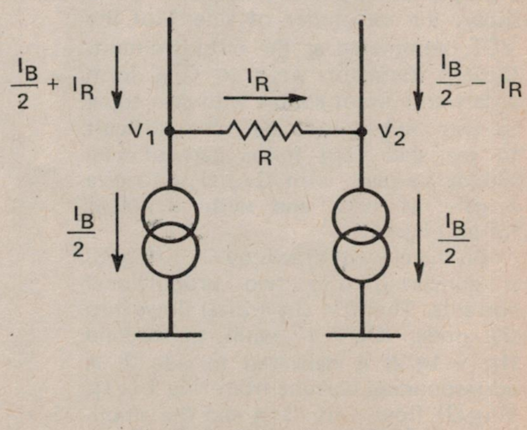


Fig. 9. Equivalent input circuit.

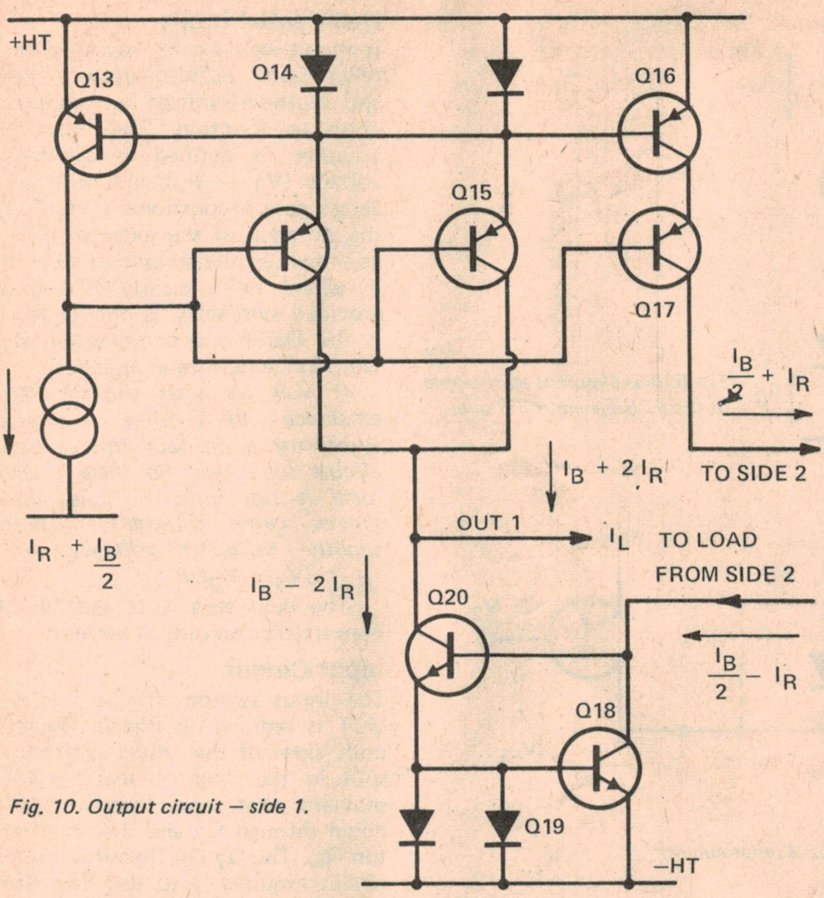


Fig. 10. Output circuit — side 1.

cause deviations from ideal behaviour due to resultant in β. In Q_{12} the base current I_{B12} (assuming constant β to first order) can no longer equal I_{B10}. Current source operation must therefore deteriorate under operational conditions.

Output Circuit

The next step is to determine how the input signal current I_R is translated into a proportional floating output. Fig. 10 shows the remainder of side 1 of the VCT, designated as the output circuit. Clearly transistors Q_{18} to Q_{20} form a derived current source with gain equal to two. But it may be more difficult to see that Q_{13} forms part of two similar sources: with Q_{14}/Q_{15} to give a gain of two, and with Q_{16}/Q_{17} for unity gain.

So the current drawn by Q_{12} (Fig. 8) is converted into two proportional currents. The first ($I_B + 2I_R$) flows into the node "OUT 1" while the second ($I_R + I_B/2$) is delivered to side 2. A corresponding current from side 2 ($-I_R + I_B/2$) flows into Q_{18} and the amplified signal ($I_B - 2I_R$) is drawn from the "OUT 1" terminal. The net current delivered to the load (I_L) is therefore $4I_R$.

In the paragraph before last, the detailed operation of Q_{14} to Q_{17} was hurriedly glossed over in order to first cover the principle of the output circuit. The diode function of Q_{14} should be familiar by now, but the reason Q_{15} has also been made with a double emitter is to keep $V_{BE})_{15}$ with ($I_B + 2I_R$) equal to $V_{BE})_{17}$ with half that current. In this way, the collector and base terminals of Q_{16} are linked by a virtual short circuit and Q_{16} is constrained to also function as a diode.

Overall Principle

When side 1 and side 2 are considered together, as in the simplified equivalent of Fig. 11, one can appreciate the overall concept of the VCT. The input signal ($V_1 - V_2$) causes a current imbalance $(V_1-V_2)/R$ to be superimposed on the null input bias levels (Fig. 9.) With current gain mixed into the process, the bias currents are then balanced out leaving a net differential load current $4(V_1-V_2)/R$ in the load (Fig. 11).

Device Properties

Each multiple emitter in the prototype VCT has been assumed to give a gain of two. Clearly, it would be simple to vary this; indeed it would appear feasible to provide gain in other parts of the circuit as well as or instead of those shown. Nevertheless, for the prototype as shown, $I_L = 4(V_1-V_2)/R$. For voltage gain, one might merely insert a load resistor R_L for a totally

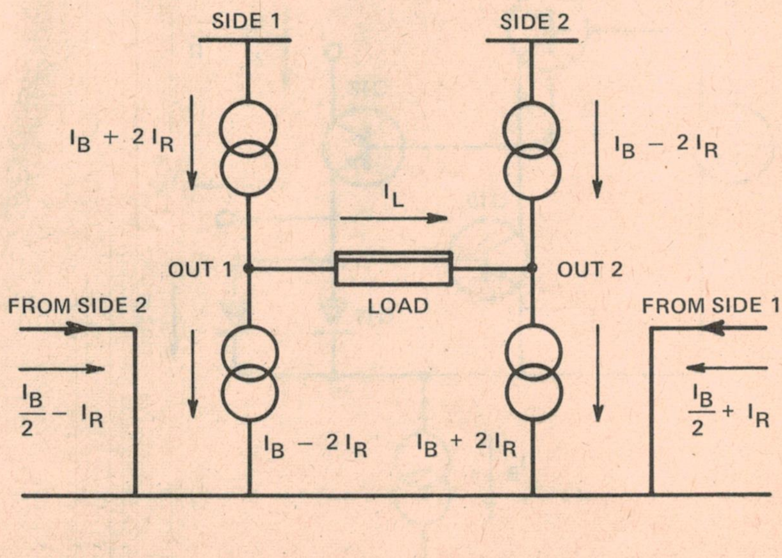


Fig. 11. Equivalent circuit of the differential current output.

floating output gain $4R_L/R$. Other elementary circuit configurations have been described by Harris.

The absolute linear range of the VCT is restricted in both current and voltage.

Transistor cutoff when $2I_R = I_B$ (see Fig. 10) limits output current $I_L = 4I_R$) to a maximum of $\pm 2I_B$, I_B being set by the circuit designer. Either output current or load is also limited by load voltage and the onset of saturation in the output transistors, i.e. the load voltage $I_L R_L$ may not exceed the total power supply range minus $4V_{BE}$. For + 15V supplies and 10mA bias current the load impedance limit is 1k4 if the full output current range is to be available. Note also that wide signal excursions from the symmetrical design bias point lead to loss of linearity, since V_{CB}'s of the current source output transistors are moved off bias values causing β to also shift. The need to maintain V_{CB} and β close to design values also limits the acceptable power supply variation — about 10 to 15% according to Harris. These figures would suggest that linearity may be seriously degraded by voltage swing well before the saturation limit is reached.

High input impedance R_{in} is a fundamental requirement of the VCT concept and is the reason for the use of Darlington inputs. To the grossest of approximations, small signal R_{in} ($= \beta_1 \beta_2 R/\beta_{10}$) is critically dependent upon the input stage current gain and maximising it leads to a whole series of tradeoffs, (e.g. R. should be low for high transconductance, β_{10} high for current source operation).

The differential output impedance works out to be roughly $1/h_{oe}$ ($h_{oe} = \partial I_C / \partial V_{CE}$ for constant I_B) and naturally the output transistors must have high collector impedances. Both input and output circuits should function near ideally, however, provided they are not unduly pushed by the circuit designer's concept of reasonable source or load impedances!

Common mode rejection ratio and required offset will both depend upon the degree of symmetry attainable in mass production but there is no reason to be pessimistic about them. High slew rates have been reported and are undoubtedly due to the fact that currents vary in only half of the circuit transistors and that the signal only proceeds sequentially through about half of these.

Conclusion

The main objective of this article has been the explanation of the principles of circuit operation. A secondary aim was to point out some unwanted second order effects and practical limitations. Such limitations occur in all devices and must not be ignored by either the designer or user.

The immediate question is whether the VCT will survive through to production or remain just another bright idea. Simplicity is a major advantage to any technological innovation and despite the plethora of transistors, the VCT is very simple in principle. Furthermore its implementation will rely totally on existing technology — its future looks bright.

I should like to thank my students whose curiosity and questions about the VCT has led directly to this article.